

The WFIRST Coronagraph Instrument: a major step in the exploration of Sun-like planetary systems via direct imaging

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ABSTRACT

The Wide Field Infrared Survey Telescope (WFIRST) Coronagraph Instrument (CGI) will be the first high-performance stellar coronagraph using active wavefront control for deep starlight suppression in space, providing unprecedented levels of contrast and spatial resolution for astronomical observations in the optical. One science case enabled by the CGI will be taking visible images and (R~50) spectra of faint interplanetary dust structures present in the habitable zone of nearby sunlike stars (~10 pc) and within the snow-line of more distant ones (~20 pc), down to dust brightness levels commensurate with that of the solar system zodiacal cloud. Reaching contrast levels below 10^{-7} at sub-arcsecond angular scales for the first time, CGI will cross an important threshold in debris disks physics, accessing disks with low enough optical depths that their structure is dominated by transport mechanisms rather than collisions. Hence, CGI will help us understand how exozodiacal dust grains are produced and transported in low-density disks around mature stars. Additionally, CGI will be able to measure the brightness level and constrain the degree of asymmetry of exozodiacal clouds around individual nearby sunlike stars in the optical, at the ~3x solar zodiacal emission level. This information will be extremely valuable for optimizing the observational strategy of possible future exo-Earth direct imaging missions, especially those planning to operate at optical wavelengths as well, such as the Habitable Exoplanet Observatory (HabEx) and the Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR).

Keywords: Exoplanets, high contrast imaging, coronagraph, debris disks, exozodiacal light

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1. INTRODUCTION

The Coronagraph instrument (CGI) on WFIRST will serve as a major technology demonstrator in preparation for future high contrast direct imaging missions dedicated to the spectral characterization of mature exoplanetary systems in reflected light and aiming to obtain optical spectra of rocky planets in the habitable zone (HabEx and LUVOIR concept studies). Indeed, CGI will demonstrate key technologies required for high contrast coronagraphy: autonomous ultra-precise (sub-nm) wavefront sensing and control, the use of large format (48x48) deformable mirrors in space, high contrast “broad-band” (>10% bandwidth) coronagraphic masks, operation of ultra-low dark current ($\sim 10^{-4}$ e⁻/pix/s) photon counting detectors (EM CCDs) in a relevant space environment (L2 orbit), post-processing of broad-band images and integral field spectrograph data at unprecedented contrast levels (at least 30x better than currently demonstrated at similar separations,

see Figure 1). Beyond the demonstration of these individual technologies, CGI will validate the whole system level performance and end-to-end model predictions for conducting high contrast imaging from a space platform.

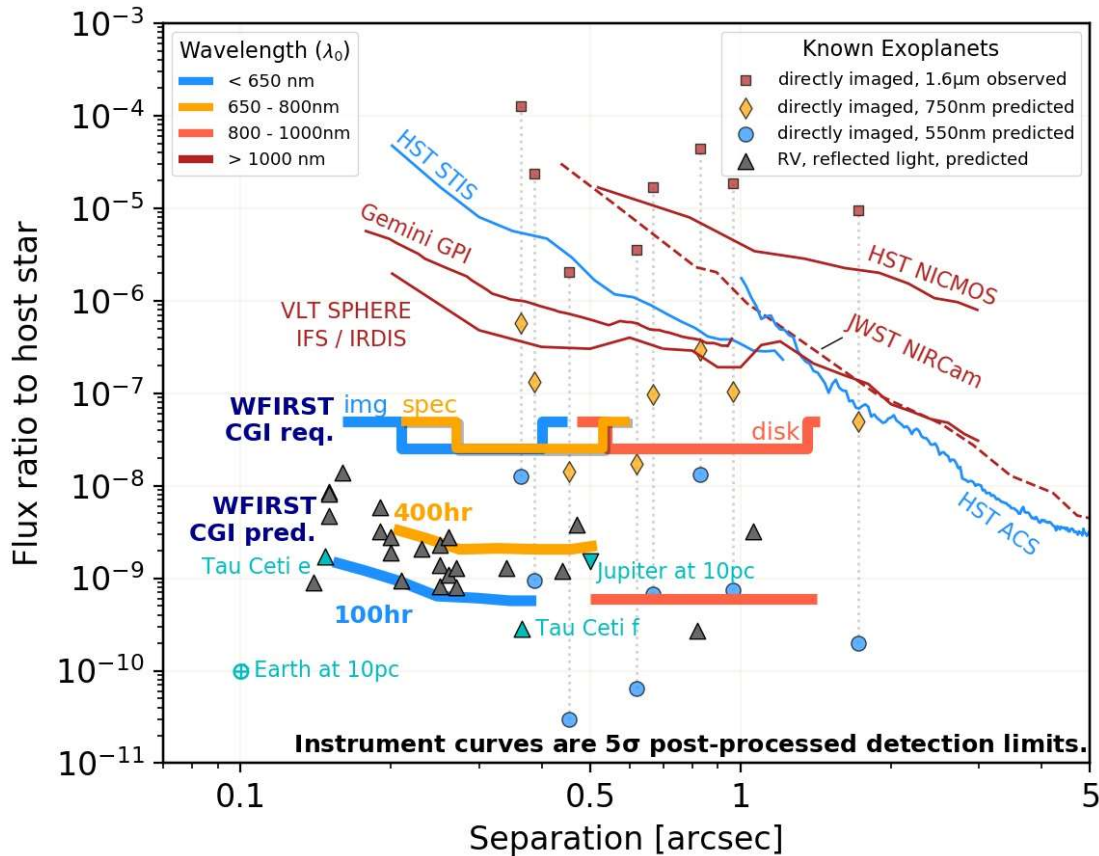


Figure 1: CGI baseline requirements and predicted CGI performance on a V=5 star, in the context of known giant planets and current instrumentation. The y-axis indicates the flux ratio between a planet and its host star (for individual planets) or between the dimmest source detectable at 5-sigma after post-processing (for instrument performance curves) and its host star. The x-axis is projected separation in arcseconds. Points and lines are color-coded by wavelength of observation. Solid and dashed lines are 5-sigma point source detection limits versus separation from the host star; these limits are calculated from post-processed data. The predicted performance for the future observatory, JWST, is plotted as a dashed line. Lines labeled "CGI pred." are current best performance predictions. Black triangular points are estimated reflected light flux ratios for known gas giant radial velocity-detected (RV) planets at quadrature, with assumed geometric albedos of 0.5. Red squares are 1.6 μ m flux ratios of known self-luminous directly-imaged (DI) planets. Dotted lines connect each DI planet's known 1.6 μ m flux ratio to its predicted flux ratio at 750 nm (yellow diamonds) or 550 nm (blue circles), based on COND or BT-Settl planet evolutionary models. Cyan points represent the reflected light flux ratios of Earth and Jupiter at 10 pc as well as super-Earths Tau Ceti e and f. Credit: Vanessa Bailey (JPL).

It will improve and inform models about key engineering aspects (e.g. DM electronics, fine pointing control systems, precision mask mechanisms), disturbances in actual space environment (including those that affect the amplitude, temporal and spatial frequencies of observed wavefront drifts), in-orbit operations (autonomous starlight suppression systems, attitude maneuvers to enable differential imaging) and data calibration (application of advanced high contrast speckles subtraction algorithms, extraction of point source positions, fluxes and spectra from real astrophysical scenes, including all detector artifacts, and recorded at the relevant flux levels).

A successful CGI technology demonstration that meets the baseline technical requirements ("BTRs") will have science capability. Figure 1 indicates the BTRs of CGI, expressed in terms of flux-ratio detection limits as a function of separation,

as well as the prediction based on current laboratory results. Obviously, the quality and magnitude of potential CGI scientific investigations will depend on the exact level of performance demonstrated during the on-orbit commissioning and CGI tech demonstration phase (predicted to be 3 months over the first 18 months of the mission). At the BTR performance level, visible images and spectra of self-luminous planets previously detected in the near-IR could be obtained, as well as images of debris disks $\sim 100\times$ fainter than those previously imaged by HST in scattered light (see section 4), and at smaller separations. If the demonstrated detection limit per resolution element is closer to a flux ratio of $\sim 10^{-9}$, as suggested by current lab-validated performance of WFIRST coronagraphs, wavefront control and detectors (Figure 1 “WFIRST CGI pred” curves), more ambitious science investigations will be possible. They include blind searches of mature giant planets seen in reflected light around nearby stars, optical spectra of mature Jupiter analogues previously detected by ground-based radial velocity (RV) observations, or the detection and spatial characterization of habitable zone dust (exozodiacal dust located in the inner part of debris disks) at $\sim 3\times$ the solar system density level. The focus of this paper is exozodiacal dust; we describe hereafter the scientific potential of CGI exozodiacal observations, and how they benefit future direct imaging missions.

2. WHAT IS (EXO)ZODIACAL DUST AND HOW DOES IT IMPACT EXOPLANET DIRECT IMAGING?

The solar system zodiacal cloud contains a population of small ($\sim 1\text{--}100\ \mu\text{m}$) warm dust grains located within the asteroid belt, extending from $<0.1\ \text{AU}$ to $\sim 3.3\ \text{AU}$. The COBE Diffuse Infrared Background Experiment (DIRBE) included measurements of the zodiacal light foreground from 1.25 to $240\ \mu\text{m}$, enabling modeling of its brightness distribution, grain size distribution, temperature, and optical depth radial profiles with high accuracy^{1,2}. While its optical depth is only 10^{-7} at $1\ \text{AU}$ and its total mass estimated to only a few 10^{-9} Earth mass—equivalent to an asteroid of $15\ \text{km}$ in diameter—the zodiacal cloud integrated flux dominates that of any planet in the solar system at any wavelength ranging from the optical to the mid-infrared (IR).

Zodiacal dust is believed to originate in asteroid collisions and the evaporation/break-up of comets as they approach the Sun. While some authors suggest that most of the observed dust is of cometary origin, e.g., created via spontaneous disruption of Jupiter family comets⁴, the relative contribution of asteroids and comets is still under debate. Similarly, “exozodiacal” dust refers to the inner ($<\text{few AU}$) warmer ($>\sim 200\ \text{K}$) part of circumstellar debris disks, where terrestrial planets form, and where we might see the signature of “exo-comets” and “exo-asteroids.” Because zodiacal dust grain lifetimes are much shorter than stellar lifetimes, it is generally believed that exozodiacal dust must be regenerated⁵ to be observed around main sequence stars. The inner brightness distribution of equivalent “exozodiacal” dust structures in debris disks around other mature stars is then expected to reflect present dust sources (comets, asteroids), as well as sinks (Poynting-Robertson drag, radiation pressure), and perturbations (collisions, evaporation, planets), revealing some of the system’s current dynamical state and formation history. In particular, bright exozodiacal disks may be the signposts of outer planets scattering numerous comets in the inner regions, similar to what happened during the solar system Late Heavy Bombardment^{4,6}.

But the presence of exozodiacal dust is really a double-edged sword. Indeed, bright exozodiacal dust structures can provide key information about the dynamical processes at play in other planetary systems, but at the same time, they may represent a significant impediment to the direct imaging and spectral characterization of planets around other stars, particularly any faint Earth-like exoplanets orbiting in their habitable zone (HZ). Considering for instance a $4\ \text{m}$ telescope viewing a Sun-Earth twin system at $10\ \text{pc}$ under 60° inclination with an exact replica of the solar zodiacal cloud, the corresponding exozodiacal dust flux *per spatial resolution element* (PSF FWHM) is a few-hundred times brighter than the Earth at $10\ \mu\text{m}$ ^{7,8}, and still ~ 3 times brighter than the Earth seen at quadrature in the visible⁹. A bright exozodiacal disk will contribute a higher background noise and increase the exposure time required for exoplanet direct detection. Realistic and optimized observing scenarios for exo-Earth direct-imaging missions¹⁰ estimate that a factor of 10 increase in exozodiacal dust density level, e.g., from solar level (1 “zodi”) to 10 times higher (10 “zodis”), reduces the exo-Earth yield of such missions by a factor of ~ 2 . While manageable, this loss in sensitivity is still significant. A potentially more problematic effect of bright exozodiacal emission is the creation of bright “clumps,” regions of density enhancement trailing and leading the planet in its orbit, as predicted by disk-planet interaction models and actually observed in the solar system¹. Simulations conducted in the case of an Earth analog embedded in exozodiacal clouds of different brightnesses¹¹ predict for instance that at a level of 20 “zodis,”

local heterogeneities in the disk could be brighter than an exo-Earth and constitute important sources of confusion and false positives. The exact location and strength of these clumps is expected to vary with planet mass, semi-major axis and outer dust characteristics, e.g., density and typical grain size¹².

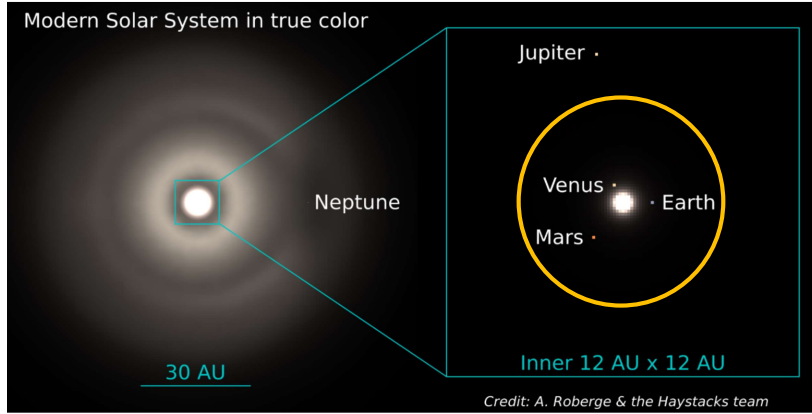


Figure 2: Model³ of the solar system as viewed pole-on in the visible with a spatial resolution of 0.03 AU per pixel and the Sun “removed”. *Left panel:* brightness scaling adjusted to highlight dust structures. *Right panel:* zoom-in of the inner region with a steeper (non-linear) brightness scaling revealing the Earth, Venus, and Mars. The solar zodiacal emission comes from regions within the asteroid belt, at the approximate distance represented by the yellow circle. Credit: Aki Roberge (NASA-GSFC) and the “Haystacks” team

However, the main result is that exozodiacal clouds at density levels of ~ 20 solar zodis or more may generate bright enough clumps to preclude the direct detection of exo-Earths, or at least make data interpretation difficult, especially for systems seen at high inclination. In highly inclined systems, we must look through a much larger column of dust to see planets, including any cold dust in the system. Although one may think this cold dust would be negligibly faint due to the $1/r^2$ illumination factor, forward scattering of light by dust grains can partially counter this effect. As a result, the surface brightness in an edge-on HZ can be dominated by dust physically located beyond a few AU instead of dust within the HZ¹³. A better knowledge of exozodiacal disk brightness level and morphology—both per individual star and in a statistical sense—plays an important role for optimizing future space missions aiming at the characterization of Earth-like exoplanets, as recognized early on^{11,14}.

3. CURRENT STATE OF KNOWLEDGE AND LIMITATIONS OF EXISTING FACILITIES

If exozodiacal clouds are similar to what is observed in the solar system, their spatially integrated flux—relative to the central star—is roughly 1,000 times brighter in the mid-IR than in the visible. For a perfect solar system analog seen pole-on for instance, the ratio of total zodiacal flux to stellar flux is $\sim 4 \times 10^{-5}$ at $10 \mu\text{m}$, compared to only $\sim 4 \times 10^{-8}$ at V band. This advantage in contrast is well known, and *in the absence of a high-contrast visible space-based coronagraph*, exozodiacal surveys have been primarily conducted in the *mid-IR*, either through space-based spectroscopic measurements, or through ground-based spatially resolved measurements.

Space-based infrared telescopes, such as the Infrared Astronomical Satellite (IRAS), the Infrared Space Observatory (ISO), and Spitzer, are too small to spatially separate the exozodiacal dust emitting region from the central star. They rely instead on spectral excess measurements, which require careful calibration and accurate subtraction of the model dependent stellar spectral energy distribution. As a result, Spitzer detection limits for exozodiacal disks are typically 100 zodis at $24 \mu\text{m}$, and 1,000 zodis at $10 \mu\text{m}$, the wavelength most sensitive to HZ dust. Only a few warm excesses have been detected by

Spitzer around mature stars above these detection limits^{15,16}. Out of 203 FG main sequence stars observed with the Spitzer InfraRed Spectrometer (IRS), only two showed an excess in the short wavelength band (8.5–12 μm)¹⁷.

To detect and characterize exozodiacal disks around a large number of sunlike stars *in the mid-IR*, significantly lower dust density levels must be accessed, and the dust-emitting region needs to be spatially resolved from the star. This calls for improvements in both contrast and spatial resolution and means that nulling interferometry is required. Three instruments have tackled this observational challenge over the last 20 years: the Multi Mirror Telescope Nuller^{18,19}, the Keck Interferometer (KI) Nuller^{20,21}, and the Large Binocular Telescope Interferometer (LBTI)^{22,23}. The KI observations reached a typical detection limit of ~ 300 to 500 zodis per star^{24,25} between 8 and 10 μm . The LBTI exozodi key science survey, which started in 2013^{26,27}, has been demonstrating further improvements in sensitivity. The statistical analysis of LBTI data obtained to date indicates with 95% confidence that the typical (median) level of exozodi emission around sunlike stars with no outer cold dust reservoir previously known is below 26 zodis²⁸. This number, which benefits from averaging over a few dozen stars, should not be confused with the detection limit *per individual star*, which is about 30 zodis for early spectral types and ~ 100 –200 zodis for solar analogs.

While LBTI data indicate that the typical level of exozodiacal dust around sunlike stars is likely below the confusion limit proposed by Defrere et al.¹¹, the LBTI detection limit *per individual* sunlike star is then still a factor of 10 above it. Additionally, there are limitations of this ground-based mid-IR approach, including bright thermal (sky) backgrounds and insufficient spatial resolution to resolve disk substructures. More importantly, basic dust properties (e.g., density profile and size distribution) cannot be uniquely derived from measurements over a narrow wavelength range. This means that the brightness of exozodiacal emission at visible or shorter IR wavelengths cannot be reliably extrapolated from mid-IR measurements alone. This last issue is clearly illustrated by the intriguing detection of $\sim 1\%$ near-IR excesses around $\sim 20\%$ of main sequence stars,^{29,30,31,32} with generally no detection counterpart in the mid-IR³³, pointing to populations of very hot and small (submicron) grains piling up very close to the sublimation radius around these stars^{33,34,35}. Visible exozodi observations are required³⁶ to measure the scattering phase function of dust grains, to better inform grain size and shape, and finally to enable connecting scattered light spectra with IR spectral energy distribution (SED) for compositional modeling.

In short, to make further progress, high-contrast, high spatial resolution space-based observations are required, ideally at multiple wavelengths. The WFIRST CGI will start this journey toward exozodiacal dust imaging and spectral characterization at low dust density levels (~ 1 –100 times solar), crossing an important threshold in debris disk physics, at a spatial resolution improved to ~ 50 mas in the visible.

4. HOW WILL CGI IMPROVE THE STATE OF KNOWLEDGE AND IMPACT FUTURE MISSIONS?

The benefits of using coronagraphy for the study of exoplanetary systems became obvious with the first optical images of beta Pictoris's extended edge-on circumstellar disk obtained by Smith & Terrile³⁷. Following the IRAS satellite discovery of a large IR excess around this star, these optical coronagraphic observations provided the first direct confirmation of planet formation and resolved images of dusty debris disks in another system. With the access to space provided by the Hubble Space Telescope (HST), many more (bright) circumstellar disks have been spatially resolved^{38,39,40,41} since. However, HST's high contrast instruments have only achieved high levels of starlight suppression at large separations, such as the 10^{-9} flux ratio detection⁴² of Fomalhaut b at $12''$. The Space Telescope Imaging Spectrograph (STIS) is the only remaining operational high dynamic range optical instrument in space today. HST/STIS does provide access to separations as small as $0.25''$ in the visible, but only at $\sim 10^{-4}$ contrast⁴³, limiting exozodiacal observations to the closest stars and again to disks with very high surface brightness, typically 10^4 higher than in the solar system.

With expected (current best predictions) point source detection limits better than 1.5×10^{-9} for angular separations from $0.15''$ to $1.46''$ at wavelengths ranging from 575 nm to 825 nm, the WFIRST CGI promises a drastic improvement in high-contrast astronomical imaging capabilities at optical wavelengths. At 575 nm for instance, a point source detection limit of 1.5×10^{-9} is expected to be reached as close as 150 mas from the star, a separation referred to hereafter as the coronagraph inner working angle (IWA). In comparison, radiometric calculations⁴⁴ indicate that for a solar system zodiacal cloud analog seen around a sunlike star at 7 pc at 575 nm and viewed under a 60 deg inclination with a 2.4m telescope, the disk flux contributed per spatial resolution element at the IWA (~ 1 AU in that case) is about 5×10^{-10} relative to the star. In other words, for a sunlike

Table 1: List of currently envisioned WFIRST/CGI science filters and observing modes, together with contrast performance best estimates (CBEs) for each. Point source detection limits indicate the flux (relative to the central star) of the dimmest point source that can be detected at 5σ or higher *anywhere* within the range of angular separations indicated. Only the 3 highlighted modes will be *fully* tested from the ground, but all filters and modes listed will be available for CGI observations.

CGI Filters	λ_{Center} (nm)	BW	Channel	Masks	Working Angle (λ/D)	Working Angle ($''$)	Point Source Detection Limit (CBEs)	Starlight Suppression Region
1	575	10%	Imager	HLC	3–9 λ/D	0.15–0.43''	1.5×10^{-9}	360°
2	660	18%	IFS	SPC	3–9 λ/D			130°
2	660	18%	Imager	SPC	3–9 λ/D			130°
3	760	18%	IFS	SPC	3–9 λ/D	0.20–0.56''	3.5×10^{-9}	130°
3	760	18%	Imager	SPC	3–9 λ/D			130°
4	825	10%	Imager	HLC	3–9 λ/D			360°
4	825	10%	IFS	HLC	3–9 λ/D			360°
4	825	10%	IFS	SPC disk	6.5–12 λ/D			360°
4	825	10%	Imager	SPC disk	6.5–12 λ/D	0.50–1.46''	6×10^{-10}	360°

star at 7 pc, the CGI detection limit corresponds to about 3 zodis at 1 AU, and would degrade to ~ 12 zodis at 2 AU, assuming the same instrument contrast at both separations and a quadratic fall-off in dust density. For sunlike stars close enough that some of their exozodiacal cloud emission can be captured outside of the CGI 150 mas IWA (i.e., located at a distance $d < \sim 20$ pc), the dust surface brightness at the physical IWA will decrease as $1/d^2$. But so does stellar flux, meaning that the minimum dust-to-star flux ratio detectable per resolution element will stay the same. As a result, for sunlike stars within ~ 20 pc, the sensitivity will be a constant 3 zodis at the IWA, reached at a physical separation of $1 \text{ AU} \cdot (d/7 \text{ pc})$. For cooler (respectively hotter) stars than the Sun⁴⁵, the exozodi surface brightness at the Earth equivalent insulation distance would be lower (respectively higher), and the detection limits in zodi units would be slightly worse (respectively better). Figure 3 shows an illustration of the exozodiacal dust disk image expected when observing a nearby sunlike star with only 10 zodis of dust with the CGI hybrid Lyot coronagraph (HLC) mask at 575 nm. Dust emission at that level is clearly detected in a couple hours, together with some of the ring structures expected to be created by in-spiraling dust trapped in resonance with the orbit of a hypothetical perturbing planet.

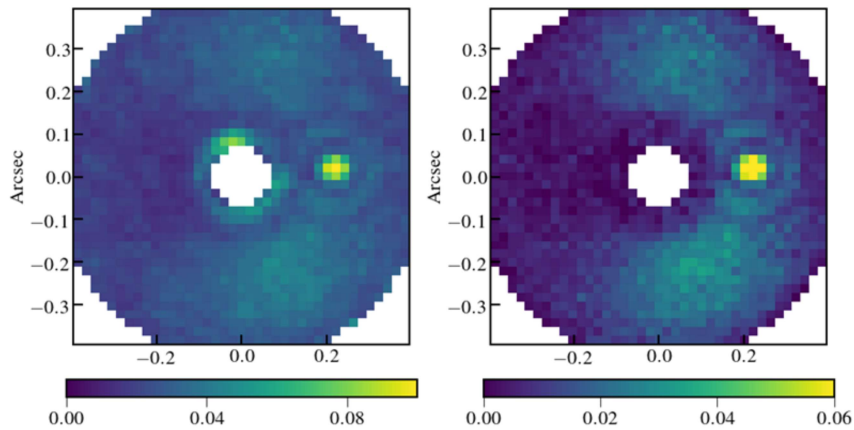


Figure 3: Simulated WFIRST CGI observations (HLC 575 nm imaging mask) of a nearby sunlike star (1 Ori, spectral type F6V at ~ 8 pc) hosting an exozodi dust cloud $10\times$ denser than in the solar system, showing resonant structures due to a hypothetical jovian planet located at 1.6 AU. The assumed instrumental parameters are consistent with the current lab-validated performance of coronagraphs wavefront control and detectors, and the detection limits listed in Table 1. Flux scale is square-root stretch in units of photoelectrons/s. Simulated exposure time is 2.8 h. (Courtesy of M. Rizzo, N. Zimmerman and the “Haystacks” team). The right image shows the contrast enhancement provided by PSF subtraction (speckles removal) using observations of a reference star. The field of view diameter is $0.8''$ in both images.

More detailed instrument simulations and disk observations DRMs will be required to better understand what debris disk physical properties can actually be extracted from CGI exozodi images and at what level of accuracy. This work can essentially be split into two parts: (a) the “inversion” of coronagraph images, i.e. deriving true disk spatial brightness distribution from simulated images, and (b) deriving basic dust grain characteristics (e.g. size distribution and scattering function) from these inverted images. The inversion process is important, as the coronagraph instrument PSF is field dependent, and that well-known response function must be taken into account for proper interpretation. In particular, and as illustrated in figure 4, the off-axis PSF varies greatly around the IWA: it goes from a very asymmetric PSF for disk regions located inside the IWA to a better behaved PSF for sources located outside of the IWA.

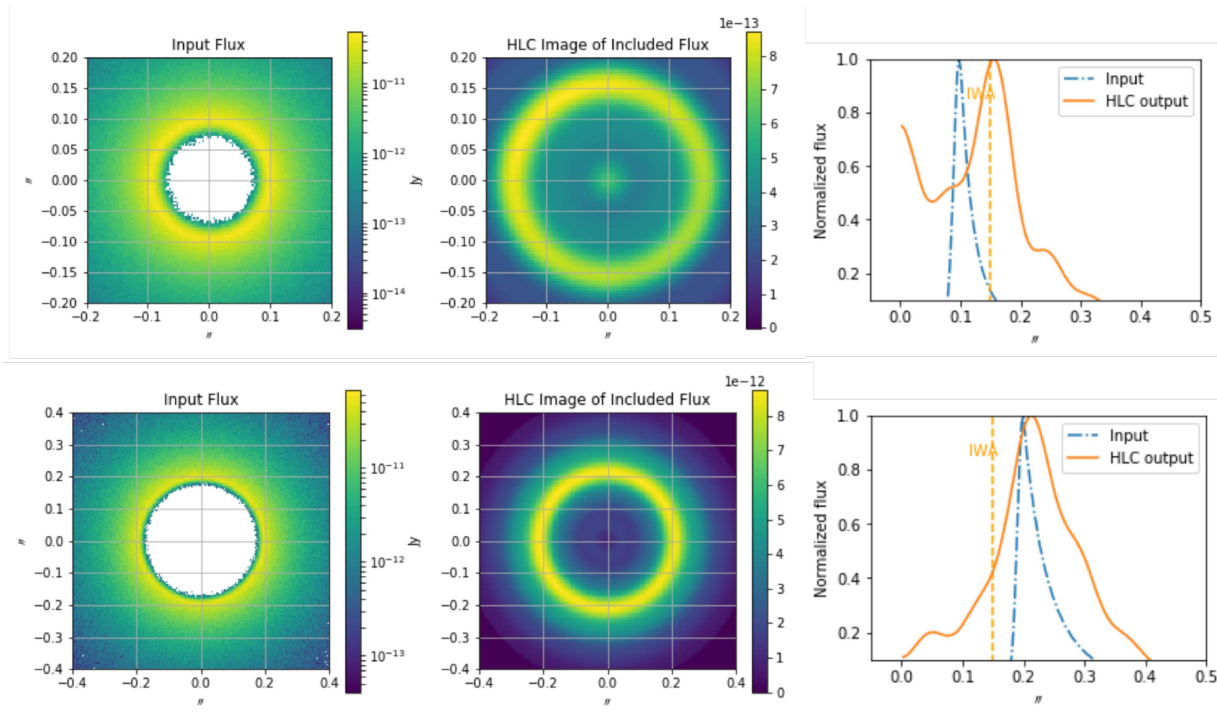


Figure 4: Simulations illustrating the effect of (HLC) coronagraphic PSF variations close to the $0.15''$ inner working angle. From left to right: input disk model, coronagraphic image and comparison of the two normalized brightness distributions (1-D cuts). Top panel: ring-like disk structure centered inside the IWA (at $0.1''$), and seen pole-on. Bottom panel: ring-like disk structure centered outside the IWA (at $0.2''$). Note the different angular scales between the top and bottom panels. In the inner ring case, most of the brightness distribution is pushed outwards, and some of the flux is sent to the very center. Credit: Ewan Douglas (MIT).

5. CONCLUSION

The simulation results shown in Figure 3 illustrate the power of conducting sensitive spatially resolved exozodiacal observations with the WFIRST CGI, searching at the same time for the presence of otherwise undetectable planets (early type stars), possibly constraining their mass and orbit via their resonant structures, or the clearing of the inner disk. CGI will offer the first opportunity to explore disk-planet interactions at low dust density levels ($\sim 3\times$ solar using current best

performance predictions), and at very small physical separations: within the snow-line of sunlike stars located within ~ 20 pc, and in the HZ of those closer than ~ 10 pc. Interestingly, this science case is very robust for 2 main reasons. First, -and conversely to the case of mature planets which have visible contrast levels limited to 10^{-8} even for the largest planets-, debris disks come with a broad continuum of dust opacity levels, surface brightness and flux ratios. Second, the current best observations of exozodi disks around sunlike stars²⁸ show detection limits of the order of 100 zodis or more, which can be reached even if CGI were only to perform at its minimum performance level (BTRs). In addition, CGI will directly measure exozodi levels and resolve their spatial structures at the visible wavelengths considered for future missions for the first time. These observations will start to establish whether the zodiacal cloud of our inner solar system is representative of the population of our nearest sunlike neighbors; this information cannot be obtained from the ground. The CGI will hence pave the way to even more capable future direct imaging missions, as illustrated by the ongoing Starshade Probe, HabEx, and LUVOIR concept studies.

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